The Predictability of Large-Scale, Short-Period Ocean Variability in the Philippine Sea and the Influence of Such Variability on Long-Range Acoustic Propagation

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LONG-TERM GOALS

The long-term goal of this project is a complete and accurate understanding of the properties of acoustic pulses sent over mesoscale to global scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals and late mode arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals. The better the understanding of the forward problem, the better acoustic data can be used to understand the ocean.

OBJECTIVES

This work aims to develop models of ocean variability for understanding and predicting long-range acoustic propagation. Models of ocean variability, and therefore the associated sound speed variability, in the Philippine Sea are to be developed from historical data and from the PhilSea'09 and PhilSea'10 experiments, or adapted from existing efforts. Emphasis is placed on distinguishing between predictable (mesoscale, internal tides) and stochastic (internal waves) variabilities. These models will be used to obtain the relevant acoustic properties (e.g., full-depth sections of sound speed) such that the effects of variability on long-range acoustic propagation can be calculated and compared to field data. The work therefore aims to develop models for the physical oceanography of the central Philippine Sea with accurate and verified acoustical and oceanographic properties and with a quantified assessment of the predictability of the various model components.

APPROACH

The general approach to better understanding acoustic propagation is a careful processing and study of acoustic data obtained on line arrays of hydrophones from acoustic propagation of over 100-5000 km ranges, acquired as part of the larger North Pacific Acoustic Laboratory (NPAL) and Philippine Sea Experiment collaborations, as well as available historical data. Many of these experiments have been conducted by Peter Worcester and Matt Dzieciuch and their group at the Scripps Institution of Oceanography. Long-range acoustic data are often analyzed in combination with other complementary in situ data that may be available, such as from thermistors or satellite altimetry. Regional or global ocean models have also been very useful in understanding the various influences on acoustic propagation. The general aim has been to use the acoustic data to test and improve such models. These models or state estimates do not resolve the ocean down to the internal waves scales that affect the acoustic propagation, however. If such models are data assimilating, then they provide an optimal synthesis of the available in situ data. This synthesis is usually better than can be obtained by

considering the data in isolation. Indeed, the optimal test of acoustic data, in situ data, and ocean models is through the combination of all these elements by data assimilation, which simultaneously tests the observations against the physical or acoustical model in a systematic and self-consistent way while reconciling the disparate data types. The modeling and state-estimates from the Estimating the Circulation and Climate of the Ocean (ECCO) group at the Jet Propulsion Laboratory have been used for these purposes; my collaborator with that group is Dimitris Menemenlis.

WORK COMPLETED/RESULTS

The recent years of this project have involved several activities and lines of research. The various facets of this project are summarized here.

Global estimates of internal tides derived from satellite altimetry. The results of a separate NASA-funded project on using satellite altimetry to derive global maps of internal tides are relevant to the analysis of the Philippine Sea data. The approach was described by Dushaw et al. (2011), who showed that the first mode of the internal tide is predictable over many regions of the oceans (Figure). "Predictable" in this case means exactly that: predictions of amplitude and phase of the internal tide using harmonic constants derived from the altimetry maps. Maps of harmonic constants, derived using a combined frequency and wavenumber tidal analysis, have been derived, which produce internal tide predictions that are in excellent agreement with the tomography observations. These forecasts or hindcasts are often O(1 decade) in the future or past from the times the altimetry data were obtained. Examples of such predictions with comparisons to tomography data in the Philippine Sea will be given next. The radiation of coherent internal tides waves far into the ocean's interior was first reported by Dushaw et al. (1995) using acoustic tomography, building from the previous work on this subject by Hendry (1977).

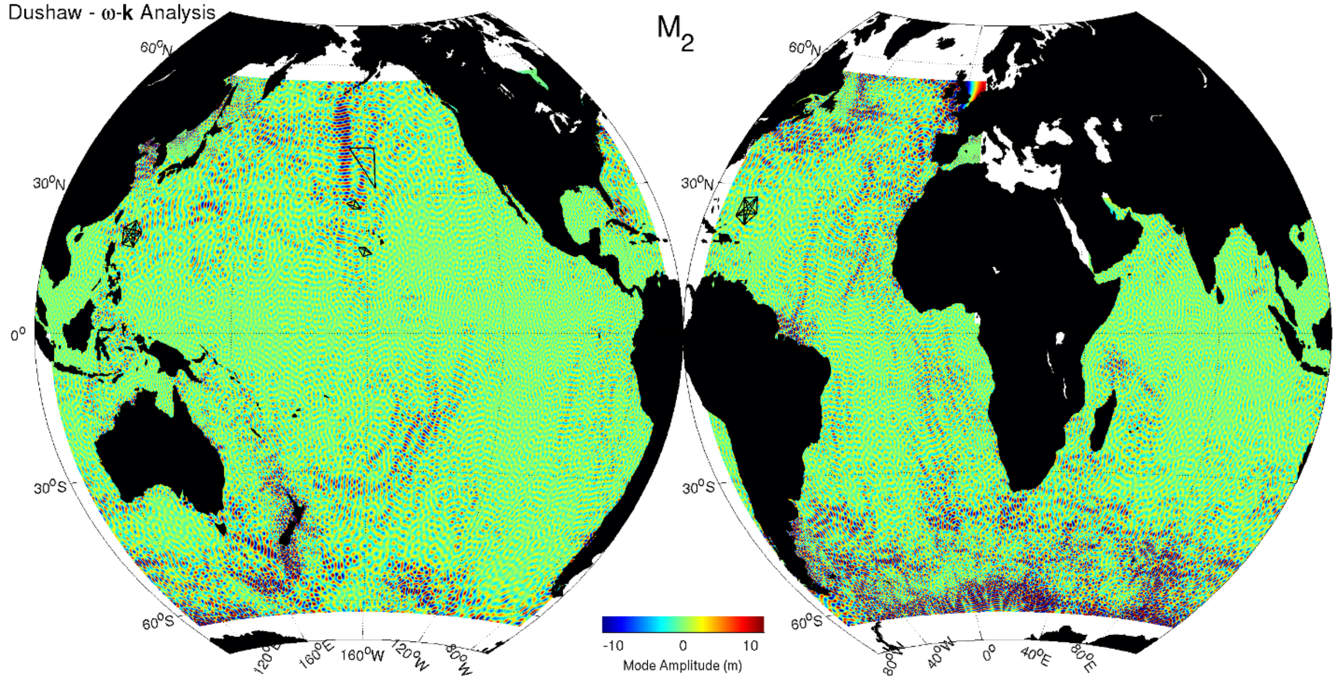

Figure Global estimates of the mode-1, M_2 internal tide amplitude derived from satellite altimetry following the frequency-wavenumber tidal analysis of Dushaw et al. (2011). These internal waves traverse ocean basins forming stable interference patterns. The mode-1 internal tide is predictable over most of the world's oceans. Tomographic observations of these waves were obtained using RTE'87 (central N. Pacific), AMODE (western N. Atlantic), HOME (Hawaii), and '09 and '10 Philippine Sea arrays, indicated. Agreement between tidal predictions from these maps and in situ observations is excellent.

Philippine Sea Tomography. Processing and analysis of the data collected during PhilSea'09 and PhilSea'10 was only completed within the past month of this writing by colleagues at the Scripps Institution of Oceanography, hence only preliminary results can be stated. The tomographic data show that the mode-1 internal tides of the region, including semidiurnal and diurnal constituents, are vigorous and highly coherent in time, however. Some degree of predictability was expected from the existing in situ observations and the altimetry analysis (Dushaw et al. 1995; Dushaw and Worcester 1998; Dushaw 2006; Dushaw et al. 2011). The initial assessment is that accurate predictions of the mode-1 internal tides - amplitude and phase of this internal wave at arbitrary points and time – are possible within the Philippine Sea basin, much like the barotropic tide is predicted now. It should be noted that the mesoscale variability in this basin is energetic, hence coherence of the internal tide here was not a foregone conclusion.

The figure below shows a preliminary regional map for the sea-surface height of M_2 internal tides of the Philippine Sea derived from altimetry. While the global map indicated above worked fairly well for predictions, it was expected that a regional map such as this would work a little better. Estimation of sea-surface height is equivalent to estimation of internal amplitude, since the internal wave modes are

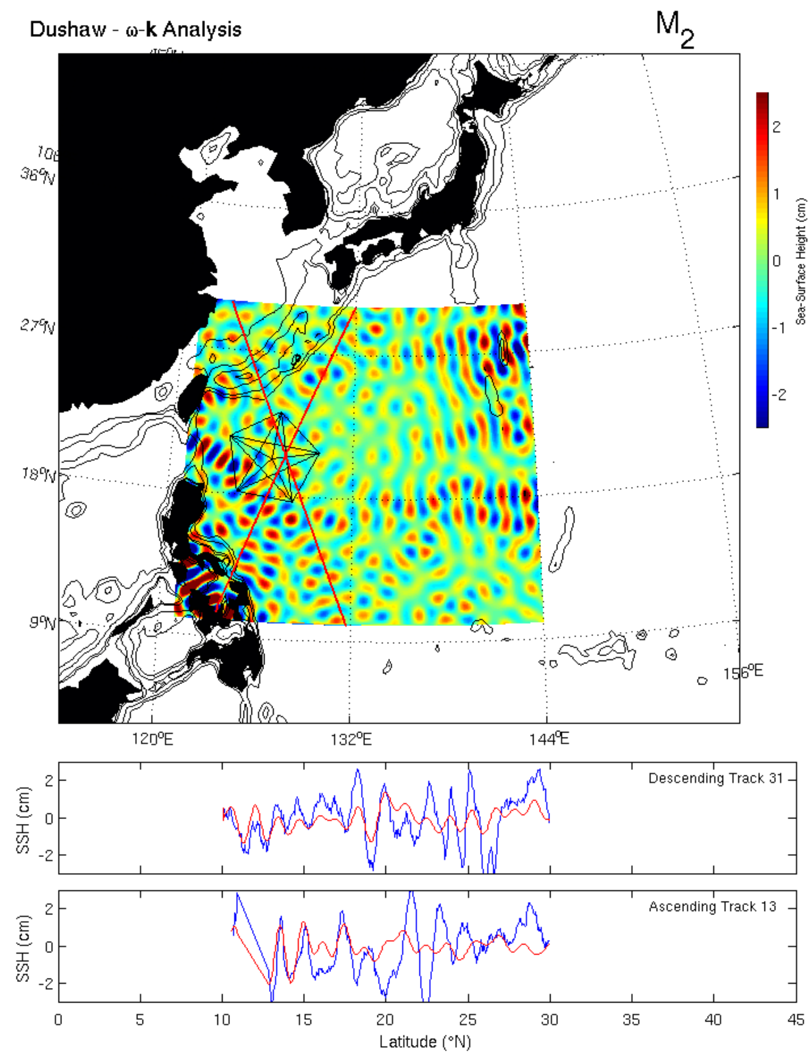

Figure (Top) Map of the M_2, mode-1 internal tide derived from altimetry, with two altimetry tracks indicated. Within the Philippine Sea the internal tide is a complicated, but coherent, interference pattern, with waves emanating from the Marianas Islands chain and the Luzon Strait, among other regions. Azimuthal equal area projection. (Bottom) Comparison of along-track (blue) and frequency-wavenumber (red) harmonic constants along the two tracks of the top panel. Ideally these two estimates would agree, but there are several possible reasons for the disagreement indicated here.

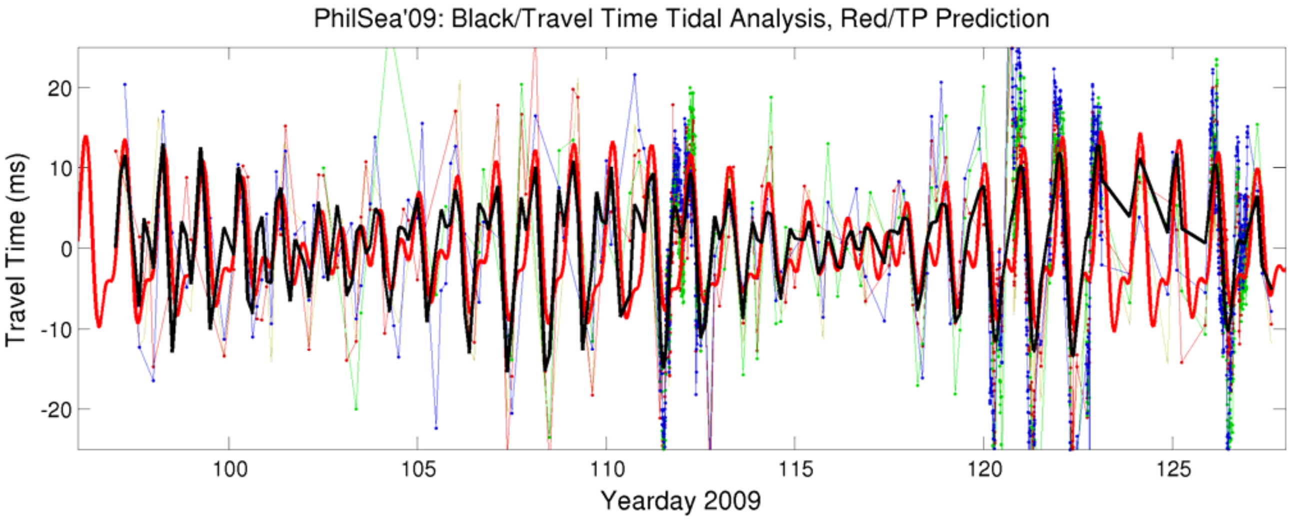

Figure   Time series of high frequency travel times measured during the '09 Philippine Sea trial experiment compared to independent predictions derived from mapped internal tides (red). The several colored lines indicate time series for the various ray arrivals on this path, with the black line indicating an average of these travel times. Altimetry data from 2000-2007 were used to obtain the predictions, hence the predictions forecast amplitude and phase a few years after the altimetry data.

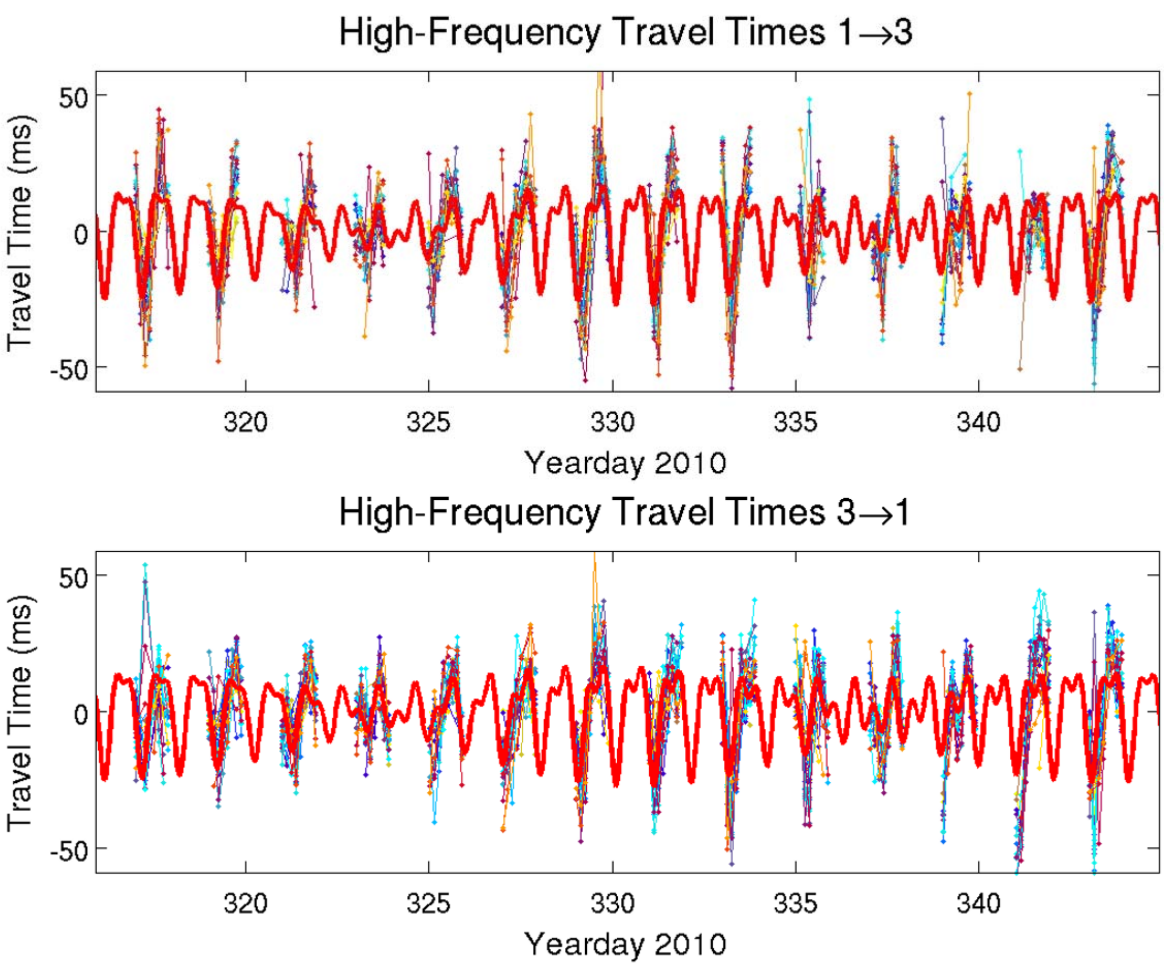

Figure Travel times obtained on reciprocal paths of the PhilSea'10 experiment compared to independent predictions. Only 30 days of a full year record length are shown. Some degree of non-reciprocity is indicated by this comparison. This 30-day record is indicative of the comparisons over the entire year record length, with occasional exceptions.

well defined. Note that this map is of a particular phase of the internal tide; for tidal predictions two such maps are required, corresponding to $A*\cos\Theta$ and $A*\sin\Theta$. Also, maps for the S_2, N_2, K_2, O_1, and K_1 constituents are obtained simultaneously.

Once the maps for the internal tide sea-surface height at the dominant tidal constituents have been obtained, it is a simple matter to compute predictions for acoustic travel time variations along particular acoustic paths and over particular time periods (Dushaw et al. 2011). A simple scale factor converts between sea-surface height and internal mode amplitude, and integration of the ray paths over the internal wave modes gives the scale factor between internal mode amplitude and ray travel time. The calculation for the prediction of tidal variation of sea-surface height is equivalent to ordinary tide prediction; the harmonic constants averaged along the acoustic path.

The figures above show such tidal predictions compared to the acoustic time series obtained during the 2009 field test (one month duration) and about 30 days of the year-long record from the 2010 Philippine Sea experiment. The predictions were derived using altimetry data from 2000-2006, so they are tidal forecasts for times several years later. The agreement between predictions and observations, amplitude and phase, is remarkable. Similar agreement is obtained over the entire year-long record, although there are instances of significant disagreement over intervals of a few days. Whether these instances are indicative of disruption of the phase and amplitude of the internal tide waves or examples of the contributions of other wavepackets (noise) is unknown. Similar agreement is also found on most of the other 14 acoustic paths, although not all paths. It is to be expected that the internal tide map derived from altimetry is not a perfect estimate. It may be expected that as the internal tide model is refined, the quality of the predictions will improve.

The spread or scatter of the ray travel times in the figures above is likely not entirely indicative of noise, but rather the different responses of the ray paths to the mode-1 perturbation. The sampling of the vertical mode by the rays is different, hence the ray travel time perturbations caused by the mode will not all be the same. Once a proper inverse of these data is computed, this different sampling will be taken into account, giving optimized, self-consistent estimates for mode amplitude. The time series of mode amplitude derived this way will be a more accurate way to compare to the independent predictions.

The coherence of the mode-1 waves apparent above and in previous comparisons is extraordinary and the result represents a revolution in our understanding of ocean variability. Not so much that the internal tide can be predicted per se, but in the way oceanographers perceive the nature of ocean variability. This revolution has unfolded rather slowly since the first report of the coherence of these waves observed by tomography in 1995 and subsequent observation of them by altimetry the following year. The consequences of this revolution and the possible applications of global estimates for mode-1 internal tides are yet to be determined.

Antipodal Acoustic Thermometry: 1960, 2004 Dushaw and Menemenlis (2014) recently completed a study to update the analysis of historical acoustic data and use these data as a measure of global-scale averaged temperature. Although this project was focused on this historical measurement of ocean climate and primarily supported by the National Science Foundation, the work drew on considerable research supported by the Office of Naval Research over the past 20 years. On 21 March 1960, sounds from three 300-lb depth charges deployed at 5.5-min. intervals off Perth, Australia were recorded by the SOFAR station at Bermuda (Figure). The recorded travel time of these signals, about 13,375 s, is a historical measure of the ocean temperature averaged across several ocean basins. The

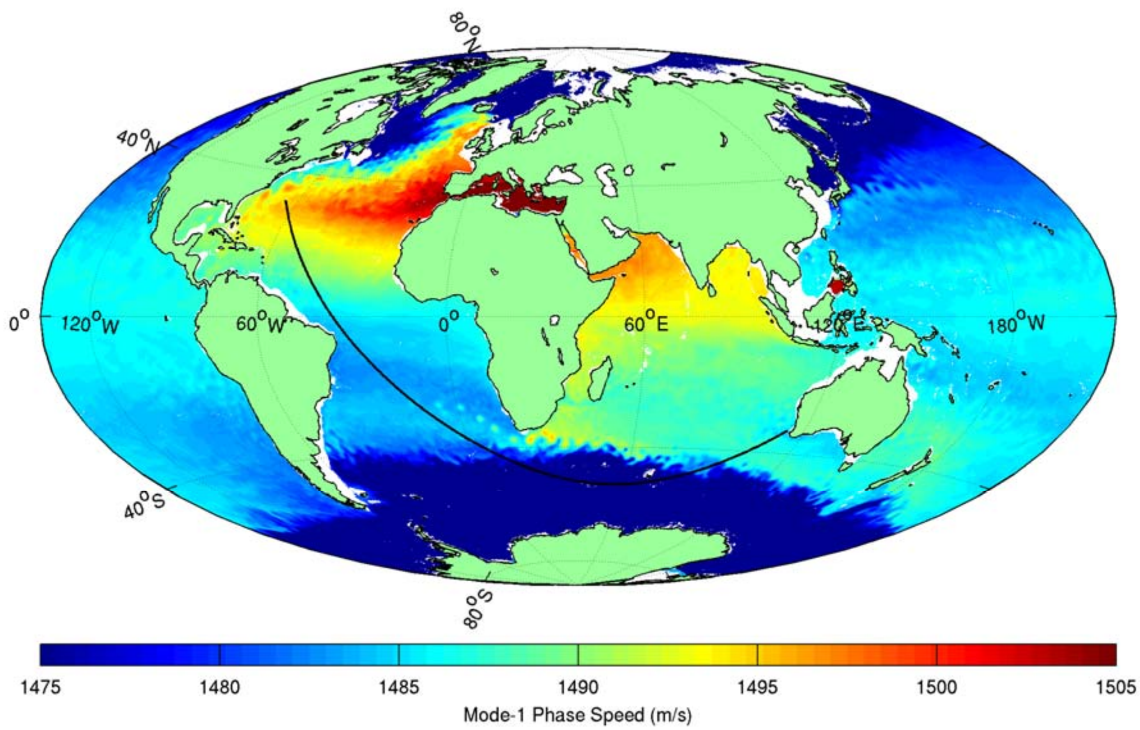

Figure Acoustic mode-1 phase speed at 15 Hz derived from the ECCO2 cube78 state estimate for August 1993. The WGS84 geodesic path between the location of the Perth shots and the Bermuda SOFAR station receivers is indicated. The phase speed is a variable strongly dependent on ocean temperature; mode-1 phase speed variations follow those of ocean temperature near the sound channel axis. The large phase speed gradients of the Antarctic Circumpolar Current and the Agulhas Rings in the South Atlantic are evident. These features have the greatest refractive influence on the acoustic paths. Hammer-Aitoff projection.

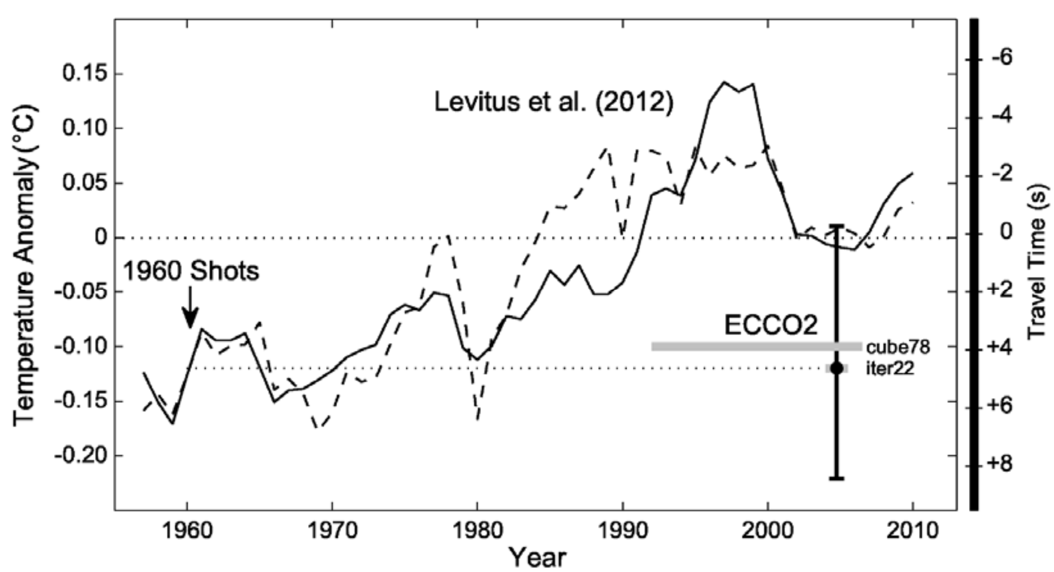

Figure A comparison of temperature anomaly computed from the hydrographic estimates of Levitus et al. (2012) to net change in temperature between 1960 and 2004 derived by Dushaw and Menemenlis (2014) using historical acoustic data from 1960 and equivalent computed acoustic travel times in 2004. The temperature is averaged over an antipodal distance (solid line: geodesic, dashed line: great circle) and near the sound channel axis. Dushaw and Menemenlis found little change in temperature, but the net uncertainties of the estimate are consistent with the hydrographic time series. Hydrographic sampling of the Southern and South Atlantic oceans was quite poor before the year 2000, and these regions are still under sampled. The error bar estimates are dominated by position error from the 1960 test and model bias from the 2004 ECCO2 state estimates.

1960 travel time measurement has about 3-s precision. High-resolution global ocean state estimates for 2004 from the "Estimating the Circulation and Climate of the Ocean, Phase II" (ECCO2) project were combined with ray tracing to determine the paths followed by the acoustic signals. The acoustic paths are refracted geodesics that are slightly deflected by either small-scale topographic features in the Southern Ocean or the coast of Brazil. The ECCO2 ocean state estimates, which are constrained by model dynamics and available data, were used to compute present-day travel times. Measured and computed arrival coda were in good agreement. Based on recent estimates of warming of the upper ocean, the travel-time change over the past half-century was nominally expected to be about minus 10s, but little difference between measured (1960) and computed (2004) travel times was found. Taking into account uncertainties in the 1960 measurements and in the 2004 ocean state estimates, the ocean temperature averaged along the sound channel axis over the antipodal paths has warmed at a rate less than 4.3 mºC/yr (95% confidence) (Figure).

Horizontal Refraction of Acoustic Tomography Signals As a corollary to the work examining the horizontal refraction of antipodal acoustic signals (Dushaw and Menemenlis 2014), it was a simple matter to finally quantify the effects of horizontal refraction on basin-scale or regional acoustic tomography in a realistic ocean environment (Dushaw 2014). As expected, such effects are so small that they can be safely ignored in practice. While a signal for long-range acoustic tomography sent between a source and a receiver follows a refracted geodesic path, most often this path is approximated by geodesic path. Since the inception of acoustic tomography, this approximation has been justified from theoretical considerations relying on estimates of horizontal gradients of sound speed or on numerical simulations employing simple theoretical models. The horizontal refraction of long-range signals was re-examined by computing acoustic propagation through global ocean state estimates obtained at 3-day intervals during 2004 from the ECCO2 project. Basin-scale paths in the eastern North Pacific Ocean employed for the 1993-2003 Acoustic Thermometry of Ocean Climate (ATOC) program and regional-scale paths in the Philippine Sea employed for observations during 2010-2011 were used as examples. For basin-scale paths, refracted geodesic and geodesic paths differ by only about 5 km, although the precise refractive effects depend on path geometry with respect to oceanographic features. Refraction causes travel times to decrease by 5-10 ms, and azimuthal angles to deviate by about 0.2 deg. At regional scales in the Philippine Sea, paths deviate from the geodesic by only 250 m, and travel times are affected by less than 0.5 ms. Such effects are not measurable and of little consequence for the analysis of tomographic data. Refraction details depend on mode number and frequency, hence the effects of horizontal refraction may contribute to the incoherence of acoustic signals.

IMPACT/APPLICATIONS

The conclusions with respect to acoustic tomography indicate a transformative development for the world's ocean observing system. While the Argo profiling float system and satellite altimetry programs are at present the cornerstone of this global observing system, it is clear that the acoustical observations will be a valuable complementary addition to these elements, giving new insights into the nature of subsurface variability of the ocean at the largest scales (Dushaw et al. 2010). The strengths of the acoustic measurement are its inherent averaging properties which no other measurement type can match. It is also clear that these disparate data types can be synthesized in an objective, systematic way through data assimilation into ocean models. The latest ocean models have sufficiently realistic acoustical properties that they offer reasonable zero-order reference states for ocean acoustic tomography. There are no technical or theoretical impediments to implementing acoustic thermometry as part of the ocean observing systems. The present system of observations and modeling aims not

only to understand ocean variability, but also to predict this variability over a variety of time scales; acoustic thermometry will be an important addition to the system for achieving these goals.

The impact and applications of the conclusion that mode-1 internal tides are predictable over most of the world's oceans have yet to be determined, but the result is revolutionary. The result should shift the way oceanographers perceive the ocean, and allow the possibility of unlooked-for coherences in other areas of ocean study. One might envision a new observation technique of internal tide tomography. NASA's Surface Water and Ocean Topography (SWOT) program aims to resolve the mesoscale motions of the world's oceans, but that resolution may not be possible without removing the internal tide “noise”. Thus, reliable global predictions for the surface signature of internal tides may be invaluable to the SWOT program.

RELATED PROJECTS

This project has been a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, which comprises researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (http://npal.ucsd.edu/)

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